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A STUDY OF THE CURRENT GROUP EVAPORATION/COMBUSTION THEORIES

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I. INTRODUCTION

Liquid fuel combustion can be greatly enhanced by disintegrating the liquid fuel into droplets, achieved by various injector configurations. Although this fact has been known for more than a century, a scientific understanding of liquid fuel spray combustion started only but forty years ago. For most part of this time, effort has been focused on single droplet combustion. A number of experiments carried out in the seventies have shown that combustion of droplet arrays and sprays do not form individual flames. Moreover, the rate of burning in spray combustion greatly deviates from that of the single droplet combustion rate. Such observations naturally challenge its applicability to spray combustion.

A number of mathematical models have been developed to evaluate the "group combustion" and the related "group evaporation" phenomena. This study investigates the similarity and difference of these models, and their applicability to spray combustion. Future work that should be carried out in this area is indicated.

II. Group Evaporation

Evaporation precedes and maintains combustion after ignition. Understanding this process is a natural first step towards understanding combustion. Two major approaches in modeling group evaporation are represented by the works of Bellan and co-workers, and Chiu and co-workers. The physical pictures that are mathematically described in these two approaches are not the same. Bellan's model is a field of uniformly distributed identical droplets with unlimited extent. The initial conditions of the droplets and the surrounding gas are given. Chiu's model is an arbitrary cloud of uniform droplets, the conditions far away from the cloud are known.

In either case, the total evaporation of the group, that being a uniform cluster or an arbitrary cloud of droplets, is the integral of the evaporation of each droplet enclosed. Therefore, the question comes back to what is the evaporation rate of each droplet, except that the "environment" in which each droplet evaporates must now be influenced by the neighboring droplets. This "environment" includes the detailed temperature, pressure, and species concentration surrounding each droplets. Given an environment, the evaporation rate of each droplet depends on its surface temperature, which is influenced by the fluid dynamic and thermodynamic processes inside the droplet.

Because the fluid/thermo-dynamic processes have been studied for a single droplet in an infinite field of gas, Bellan's work concentrates on incorporating realistic boundary conditions located at the edge of a "bubble" surrounding each droplet. The bubbles subdivide the whole space occupied by the mixture of droplets and

the gas. Spatial variations of any variables inside each bubble and the droplet are carefully studied. The possible variation of any variable from one bubble to the other is not incorporated. This work has later been extended to a moving spherical cluster, and to finite kinetics of evaporation. Among many important results, several major findings are:

1. D^2 -t law for droplet size reduction does not apply at a surprisingly lean condition.
2. Evaporation time can be an order of magnitude higher than that predicted from the single droplet case.
3. Saturation occurs at a much leaner condition than that predicted from the single droplet theory.
4. The above effects are significant even for very dilute clusters, provided that the gas phase is fuel rich.

Chiu's work, on the other hand, puts more emphasis on the thermodynamic interaction between the inside and outside of the cloud. Spatial gradient of all variables in the gas phase is modeled. But the droplets are considered as point sources of vapor. The fluid/thermo-dynamics within the droplets are ignored. The evaporation rate of each droplet is considered to be influenced by the "bubble" size, the near neighbors, and the far neighbors that constitute the "ambient" conditions. The bubble size, the extent and distribution of near neighbors are both functions of the droplet volume concentration. An important concept defined by the "group number" is used in the analysis. This number G (=evaporation time/diffusion time) controls the deviation of the group evaporation from single droplet evaporation. Important results are:

1. D^2 -t law does not apply. Which agrees qualitatively with Bellan's result.
2. The spatial gradients of all variables from any given droplet outward depend strongly on the group number. For a transient process, this gradient is important even for very small group numbers.

III. GROUP COMBUSTION

Mathematical studies of group combustion began with Suzuki and Chiu. The physical picture is a spherical cloud surrounded by the oxidizer gas with given condition far away from the cloud. This picture is the same as that in Bellan's evaporation model, except that the internal gradient of variables are modeled inside the cloud. However, the droplet's own fluid/thermo-dynamics are again neglected. All droplets are treated as fuel vapor sources only. Important results include:

1. High group number condition dominates most practical operation

conditions in a combustor.

2. As the group number increases, only a thin layer of droplets in the cloud participates in burning. This fact may complicate the picture of incomplete burning.

Labowsky and Rosner also studied the group combustion phenomenon. They assumed a cubic lattice of point droplets. Although the analysis is different, they obtained essentially the identical group number as Chiu. The analysis of Labowsky and Rosner however covers the entire range from incipient group combustion (droplets at the center of a cloud start to share flame) to total group combustion. An interesting result of their work is that a small difference of group number can trigger the jump from individual combustion to group combustion. This may be important to the stability of combustion process.

IV. CONCLUSIONS

It is clear from the above modeling effort that group evaporation/combustion impacts combustor performance. This phenomenon can be rigorously analyzed. For group evaporation, each of the two current approaches has its strong and weak points. They are summarized below.

Bellán

Strong Points- Detailed fluid/thermo-dynamics of droplet/environment interaction. Easy to incorporate aerodynamic, thermal and chemical effects rigorously.

Weak Points- No spatial gradient in the cluster of droplets. Analysis is restricted to a single cluster. No indication of how to extend it to a spray.

Chiu

Strong Points- Spatial gradient inside a cloud of droplets is included. In the later work, spray evaporation is modeled based on the earlier single cluster concepts.

Weak Points- Droplet's own fluid/thermo-dynamics are ignored. Extension to spray combustion from the group evaporation is not clear.

Furthermore, neither of the two have experimental data for validation.

Based on their strong and weak points, it is clear that Bellán's analysis is applicable to larger droplets (compared with the local spray size), colder droplet temperature, hence the region closer to the spray injector. Chiu's analysis, on the other hand, applies to fine droplets, larger spray size, nearly boiling droplet

temperature, hence the region further downstream from the injector.

At this point, a group combustion theory only exists for the ideal case of a single cluster. There is no model for a true spray.

V. RECOMMENDATIONS

Recommended future analyses are summarized below.

1. Improve the existing models by combining the strong points of both approaches.
2. Relax the assumptions made in current models, such as constant mass and heat diffusion, negligible aerodynamic effects, infinite evaporation kinetics, infinite reaction rate, single step reaction, negligible radiation. Prioritizing the above should precede the analysis if possible.
3. Begin spray combustion analysis based on the single cluster idea. The group evaporation idea has been applied to spray evaporation by Chiu. However, extension from single cluster combustion to spray combustion has not been done. Combustion adds not only heat, but also changes the distribution of oxidizer and fuel concentrations in the spray. The picture obtained from pure evaporation cannot be translated to spray combustion easily.
4. Need more experimental work. First, mathematical modelers need experimental observations to assist creating a correct physical picture. Second, data obtained from experiments are necessary for model verification. Carefully designed basic experiments should go side by side with true spray combustion experiments, because in a true spray, the simultaneous heat, mass, momentum and chemical processes all interact together. The data obtained represents the bulk effect. It is impossible to use it for differentiating the degree of importance of each individual mechanism. Prototype experiments should be done primarily for observation. Only at the final stage, when modeling is "completed", can prototype results be used for model verification. Basic experiments designed for studying a few number of mechanisms at a time will have to be done to assist and verify the modeling at the building stage.

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